

RUNAWAY STARS IN THE GUM NEBULA

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Abstract

We propose that the two pulsars PSR 0833-45 (the Vela pulsar) and MP 0835 are runaways from a common binary system originally located in the B association around γ Velorum. We present arguments in favor of a simple model of the Gum Nebula in which two distinct ionized regions are present. The first consists of the Strömgren spheres of γ Velorum and ζ Puppis while the second is a larger, more filamentary region ionized by the supernova explosion associated with PSR 0833-45. Using this model and the available dispersion measures, we estimate the distances to the two pulsars and they are found to be compatible with a runaway origin. The position angle of the rotation axis of PSR 0833-45 is also compatible with a runaway origin. The masses of the parent stars of the two pulsars can be deduced from the runaway star dynamics and an assumed age for MP 0835. We conclude that the masses of the parent stars were in excess of $10 M_{\odot}$. The dynamically-determined parent star masses are in agreement with the values one would expect for evolved members of the B association around γ Velorum. Several observations are suggested which can further test this runaway star model for these two pulsars.

Runaway stars are produced when a supernova occurs in a binary star system. This process is illustrated schematically in Figure 1. Initially, we have two massive stars with masses M_1 and M_2 in a close binary system. Such systems typically have nearly circular orbits and M_1 and M_2 may have orbital velocities of the order of 100 km sec^{-1} . M_1 is the more massive of the two stars and evolves first, eventually becoming a supernova. In the supernova explosion of M_1 a neutron star of mass M_{N1} is produced and a shell of matter of mass $(M_1 - M_{N1})$ is ejected. Figure 1a shows the initial binary system (M_1, M_2) , Figure 1b shows the ejection of the shell of matter which is presumed to take place in a time that is short compared with the orbital period of (M_1, M_2) . Once the shell has expanded beyond the position of M_2 , as in Figure 1b, it no longer exerts any gravitational force on M_{N1} and M_2 . So M_{N1} and M_2 move freely under their mutual gravitational attraction and as initial conditions have their initial separation and their initial orbital velocities. If more than half of the total initial mass of the binary system is ejected, then simple virial theorem arguments show that M_2 and M_{N1} will follow unbound trajectories. Thus, the resulting system becomes unbound if

$$M_1 - M_2 > 2M_{N1}.$$

In this case, the trajectories of M_{N1} and M_2 are as depicted in Figure 1c. Both are left as runaways with translational velocities comparable with their initial orbital velocities. Note that both M_2 and M_{N1} move off the diagram in the upward direction so as to balance the momentum in the downward direction carried away by the ejected matter of the supernova explosion.

Zwicky (1957) and Blaauw (1961) have proposed that the high-velocity O and B "runaway" stars are in fact stars like M_2 which have escaped from binary systems in the manner described above. These "runaway" stars are found to have space velocities in the range $40 \text{ km sec}^{-1} < V < 200 \text{ km sec}^{-1}$ and are always single stars that have normal spectra. Often such a runaway star is found to be moving directly away from a known O association. Blaauw (1961) and Boersma (1961) have made a very careful study of runaway stars as escapees from binary systems and this explanation is now generally accepted.

After a time T , which one can take to be essentially the difference in main-sequence lifetimes of M_1 and M_2 , the star M_2 will reach the end of its life and become a supernova, ejecting most of its mass and forming a neutron star of mass M_{N2} . Thus, both M_{N1} and M_{N2} are left as high velocity objects. We would accordingly expect many pulsars to be high-velocity runaways with velocities in the same range as those of the runaway stars found by Blaauw.

Gunn and Ostriker (1970) noticed that the older, longer-period pulsars are found at generally greater distances from the galactic plane than the younger, shorter-period ones. After a careful statistical study they concluded that the data were best fit by assuming that the parent stars of the pulsars had a scale height of $\sim 80 \text{ pc}$ and that the pulsars received velocities of the order of 100 km sec^{-1} at birth. The scale height of the parent stars corresponds to that of the massive, Population I O and B stars, which have a scale height of $\sim 50 \text{ pc}$ (O'Connell 1958) and the high velocities are explained by the runaway-star process.

Recent radio studies of interstellar scintillations of pulsars have confirmed that they are high velocity objects. Ewing *et al.* (1970) measured three pulsars and deduced that all three possess transverse velocities of approximately 100 km sec^{-1} with respect to the interstellar medium. Since interstellar medium velocities with respect to the earth are much smaller than this, they concluded that the effect was due to the motion of the pulsars with respect to both the interstellar medium and the earth. Lang (1971) has obtained similar observational results.

PSR 0833-45 (the Vela pulsar), and MP 0835 appear to be runaways from a binary system originally located in the B association around $\gamma \text{ Vel}$. Using the

nomenclature introduced above we wish to identify the old pulsar MP 0835 (period = 0.765 sec) with M_{N1} and the young Vela pulsar PSR 0833-45 (period = 0.0892 sec) with M_{N2} .

In a recent paper Brandt *et al.* (1971) have proposed that the Gum Nebula is a fossil Strömgren sphere produced by the supernova that gave birth to the Vela pulsar and the Vela X supernova remnant.

Brandt *et al.* described a photometric survey of the region around γ Vel and reported a B association around it. They list 10 stars, all having a distance of approximately 460 pc and all having spectral types earlier than B3. These stars form a cluster with a diameter of about 8° centered on γ Vel. All the stars listed must have masses in excess of $7 M_\odot$ which is the approximate mass of a B3 V star. The 07 star which is a component of γ Vel must have a mass of the order of $35 M_\odot$. This cluster appears too young to have any definite turn-off point in its Hertzsprung-Russell diagram. Surely any evolved star associated with this group such as the parent star of the Vela pulsar must have been a massive star, probably with $M > 10 M_\odot$.

Now the Vela pulsar and MP 0835 both lie just off the N.E. edge of the B association found by Brandt *et al.* (see Figure 2), making them good candidates for runaways from the association. We know that the distance to γ Vel and its B association is 460 pc (Brandt *et al.* 1971) so to establish our runaway case we need to determine the distances to the Vela pulsar and MP 0835.

Brandt *et al.* noticed that the dispersion measure of the Vela pulsar is roughly half of that of nearby pulsars and concluded that the Vela pulsar is at the center of the ionized region corresponding to the Gum Nebula. This seems very reasonable. Using averages of 21-cm data, they concluded that the neutral hydrogen density in the vicinity of the sun is $n_H \sim 0.4 \text{ cm}^{-3}$. From Ly α absorption in γ^2 Vel and ζ Pup they concluded that there is ~ 60 pc of neutral hydrogen between us and the front edge of the Gum Nebula. They then assume that the Vela pulsar lies at a distance of 460 pc as does γ Vel. So the ionized region corresponding to the Gum Nebula is found to have a diameter of ~ 800 pc.

There is strong evidence against such a large ionized region. Its angular extent would be such as to cover almost half of the sky. This is much larger than the extent of the strong H α emission from the Gum Nebula which one can observe in An Atlas of H-alpha Emission in the Southern Milky Way (Rodgers *et al.* 1960). We see that, if we include the prominent filaments north of the galactic plane as part of the nebula, then the Gum Nebula is roughly circular in shape and lies between approximately $-18^\circ < b_{II} < 18^\circ$ and $241^\circ < \ell_{II} < 277^\circ$. So it has an apparent radius of approximately 18° . This H α emission would

certainly seem to define the size of the ionized region. Also if the ionized region were as large as Brandt *et al.* suggest, then we would expect to find a significant amount of ionized matter between us and CP 0834, which lies about 45° from the center of the Gum Nebula. Lang (1971), from interstellar scintillation studies, found that the distance to CP 0834 is about 362 pc and from its dispersion measure he concluded that the mean electron density along the line of sight is $\langle n_e \rangle = 0.035$. This is just the value one obtains for neutral hydrogen regions. In addition, PSR 0628-28 and MP 0818 which are both about 30° from the center of the Gum Nebula show dispersion measures less than half that of the Vela pulsar (Terzian 1970). Thus, it seems likely that the ionized region of the Gum Nebula is confined to the region outlined by the $H\alpha$ emission and has an apparent radius of about 18° .

We can obtain a consistent model if we use a better estimate of the local neutral hydrogen density. Jenkins and Morton (1967) have measured $Ly\alpha$ absorption between the sun and three stars in Orion at a distance of 460 pc and found a mean column density of $1.6 \times 10^{20} \text{ cm}^{-2}$. This corresponds to a mean neutral hydrogen density along the line of sight of $n_H \sim 0.1 \text{ cm}^{-3}$. Since γ Vel and the Gum Nebula are in the same general area of the sky, the above value seems to be the best one to take for the neutral hydrogen density between us and the near edge of the Gum Nebula. Smith (1970) and Jenkins (1971) have also measured the hydrogen column density to ζ Pup and found $7 \times 10^{19} \text{ cm}^{-2}$. With $n_H = 0.1 \text{ cm}^{-3}$, this means that the near edge of the Gum Nebula lies at a distance of 230 pc from the sun. If we assume the Gum Nebula is spherical, then its center is at a distance of $330 \text{ pc} = 230 \text{ pc} / (1 - \sin 18^\circ)$ and its radius is 100 pc. The center of the Gum Nebula is thus 130 pc closer to the sun than γ Vel and ζ Pup and therefore does not seem to have been produced by them (see Figure 3). The only other reasonable source for ionizing the Gum Nebula is the Vela X supernova event which gave birth to the Vela pulsar as Brandt *et al.* (1971) have pointed out. The ionization could have been caused either by photons below the Lyman limit or by low-energy cosmic rays from the supernova. The age of the Vela pulsar is estimated to be 1.1×10^4 yrs. by Reichley, Downs, and Morris (1970). With the supernova event occurring only this long ago, Brandt *et al.* (1971) have shown that recombination within the Gum Nebula has not yet occurred.

Thus, we find that PSR 0833-45 (the Vela pulsar) is at the center of the Gum Nebula and lies at a distance of 330 pc from the sun. (Note: even if the Vela pulsar has a velocity of 100 km sec^{-1} it has had time to move only 1 pc since its birth.) This distance estimate is certainly consistent with the distance estimate of 500 pc to the Vela X supernova remnant according to Milne (1968 a,b) because of the great uncertainties in Milne's estimate.

The Vela pulsar has a dispersion measure of $69.2 \text{ cm}^{-3} \text{ pc}$ (Ables et al. 1970). We expect $\langle n_e \rangle \sim 0.03 \text{ cm}^{-3}$ in the neutral hydrogen region between us and the Gum Nebula, so within the large spherical nebula region we find $\langle n_e \rangle \sim 0.63$. Using this value we find that MP 0835 with a dispersion measure of $120 \text{ cm}^{-3} \text{ pc}$ (Terzian 1970) lies at a distance of $\sim 410 \text{ pc}$ from the sun. (Note: the distances of the Vela pulsar and MP 0835 have been determined completely independently of any assumptions regarding their connection with the B association around $\gamma \text{ Vel.}$)

$\gamma \text{ Vel}$ (WC8 + 07) with its B association and $\zeta \text{ Pup}$ (05) will each produce Strömgren spheres somewhat less than 50 pc in radius behind the Gum Nebula and joining with it if the local hydrogen density is of the order of $\sim 3 \text{ cm}^{-3}$ (Spitzer 1968). This additional ionization at higher density would explain the increased $H\alpha$ emission observed in the half of the Gum Nebula south of the galactic plane near these stars.

The above model of the region fits all the observations and also provides the expected increase in hydrogen density (from 0.1 cm^{-3} to 0.63 cm^{-3} to 3 cm^{-3}) as we approach the star-forming region of the young B association.

We now know the distances and the positions in the sky of the center of the B association ($\gamma \text{ Vel}$), the Vela pulsar, and MP 0835, so we can compute the lengths of the sides of the triangle they form in space and check our runaway hypothesis. The Vela pulsar is obviously the younger of the two pulsars and thus corresponds to M_{N2} , while MP 0835 corresponds to M_{N1} . The runaway star dynamics (Gott, Gunn and Ostriker 1970), tell us that if they shared a common binary origin, the two pulsars and $\gamma \text{ Vel}$ (taken to be their approximate point of origin) should form a right triangle in space, with the right angle at MP 0835. The results are as follows: the sides of the triangle are approximately 80 pc , 90 pc , and 130 pc , the angle at MP 0835 is $\sim 100^\circ$ and the angle at $\gamma \text{ Vel}$ is $\sim 40^\circ$, see Figure 1c and Figure 3.

Considering the uncertainties in the distances involved, this is a good agreement with the prediction offered by the runaway star dynamics.

We can make one check of the model immediately. Close binaries preferentially have rotation axes perpendicular to the orbital plane of the binary system. If no significant torques occur in the supernova explosions then the pulsars should have their rotation axes approximately perpendicular to the initial orbital plane, which is also the plane of the right triangle discussed above. We can compute that to be perpendicular to this plane, the rotation axis of the Vela pulsar should have a position angle in the sky of approximately $\theta = 300^\circ$. Now if pulsars are oblique magnetic rotators (Gunn and Ostriker 1969) and if the pulses originate

in the regions of the magnetic poles, then a simple geometrical model such as proposed by Wampler, Scargle, and Miller (1970) shows that the linear polarization of the pulse should sweep in position angle as the magnetic pole rotates by our line of sight. Radhakrishnan *et al.* (1969) have observed just such a classic pattern in the Vela pulsar; the linear polarization in the pulse sweeps through 45° in position angle during the pulse. The simple geometric models mentioned above also indicate that if the pulse is exactly centered over the magnetic pole, then the position angle of the average intrinsic linear polarization should be perpendicular to the position angle of the rotation axis of the pulsar. Ekers *et al.* (1969) have taken out the Faraday rotation to find the position angle of the intrinsic linear polarization of the Vela pulsar. From this we deduce an "observed" value of the position angle of the rotation axis: $\theta = 327^\circ \pm 6^\circ$ which agrees satisfactorily with our predicted value of $\theta = 300^\circ$. Uncertainties are introduced by the fact that the pulsar axis may not be perpendicular to the orbital plane and by the fact that the pulse may not be located exactly over the magnetic pole, which introduces an observational uncertainty of about $\pm 1/2$ (45°).

The difference in main-sequence lifetimes of the parent stars of MP 0835 and the Vela pulsar (M_1, M_2), is essentially equal to the age of MP 0835. If we knew this age we could compute the masses of the two parent stars M_1 and M_2 . We assume that $M_{N1} \sim 1.5 M_\odot$. The runaway star dynamics gives us one relation between M_1 and M_2 , while the difference in main-sequence lifetimes as a function of M_1 and M_2 gives us another. The rate of change of the period of MP 0835 has not been reported, so we cannot estimate its age directly. MP 0835 has a period of 0.765 sec and we might expect its age to be similar to that of other pulsars with similar periods. Now HP 1508 and CP 0329 are two such pulsars with periods of 0.740 sec and 0.715 sec respectively and ages ($\frac{1}{2} P(dP/dt)^{-1}$) of 2.3×10^6 years and 5.5×10^6 years respectively. It seems reasonable to suppose that the age of MP 0835 lies in this range. If the age of MP 0835 is approximately 6×10^6 years, then we would find $M_1 \sim 20 M_\odot$ and $M_2 \sim 10 M_\odot$; if the age is approximately 2×10^6 years then we would find $M_1 \sim 50 M_\odot$ and $M_2 \sim 30 M_\odot$.

Since we do not expect MP 0835 to be much older than 6×10^6 years, it is clear that M_1 and M_2 must both be more massive than $10 M_\odot$; this is what one would expect from the masses of the unevolved stars in the B association. If MP 0835 is a fairly young pulsar with an age of say 2×10^6 years, then M_1 and M_2 were just about as massive as the most massive unevolved stars we see in the cluster. Either result would be possible because the association is so young. An experimental determination of the rate of change of the period of MP 0835 would allow us to estimate its age and determine the parent star masses.

Several observational tests of the possible binary origin of the Vela pulsar and MP 0835 can be made. The position angle of the rotation axis of MP 0835 can be deduced from measurements of its linear polarization at different frequencies. If it is from the same original binary system as the Vela pulsar we would expect its rotation axis to be approximately parallel to that of the Vela pulsar. Secondly, the transverse velocities of the Vela pulsar and MP 0835 can be measured by interstellar scintillation techniques and compared with the predictions offered by the binary origin model. Finally our distance estimates for the two pulsars, based on dispersion measures, can be complemented by distance estimates from interstellar scintillation techniques.

In conclusion, we propose that the Vela pulsar and MP 0835 are runaways from the B association around γ Vel. Taking a simple model of the Gum Nebula it is possible to use the dispersion measures to find the distances of the two pulsars. Their positions in space found in this way are consistent with a common origin as runaways from a binary system in the B association. The masses of the parent stars of the two pulsars are found from this model to be in excess of $10 M_{\odot}$ which is consistent with what we would expect from the unevolved stars in the B association. The observed position of the rotation axis of the Vela pulsar is consistent with this binary origin model. We also propose additional observational tests of the model.

Acknowledgments

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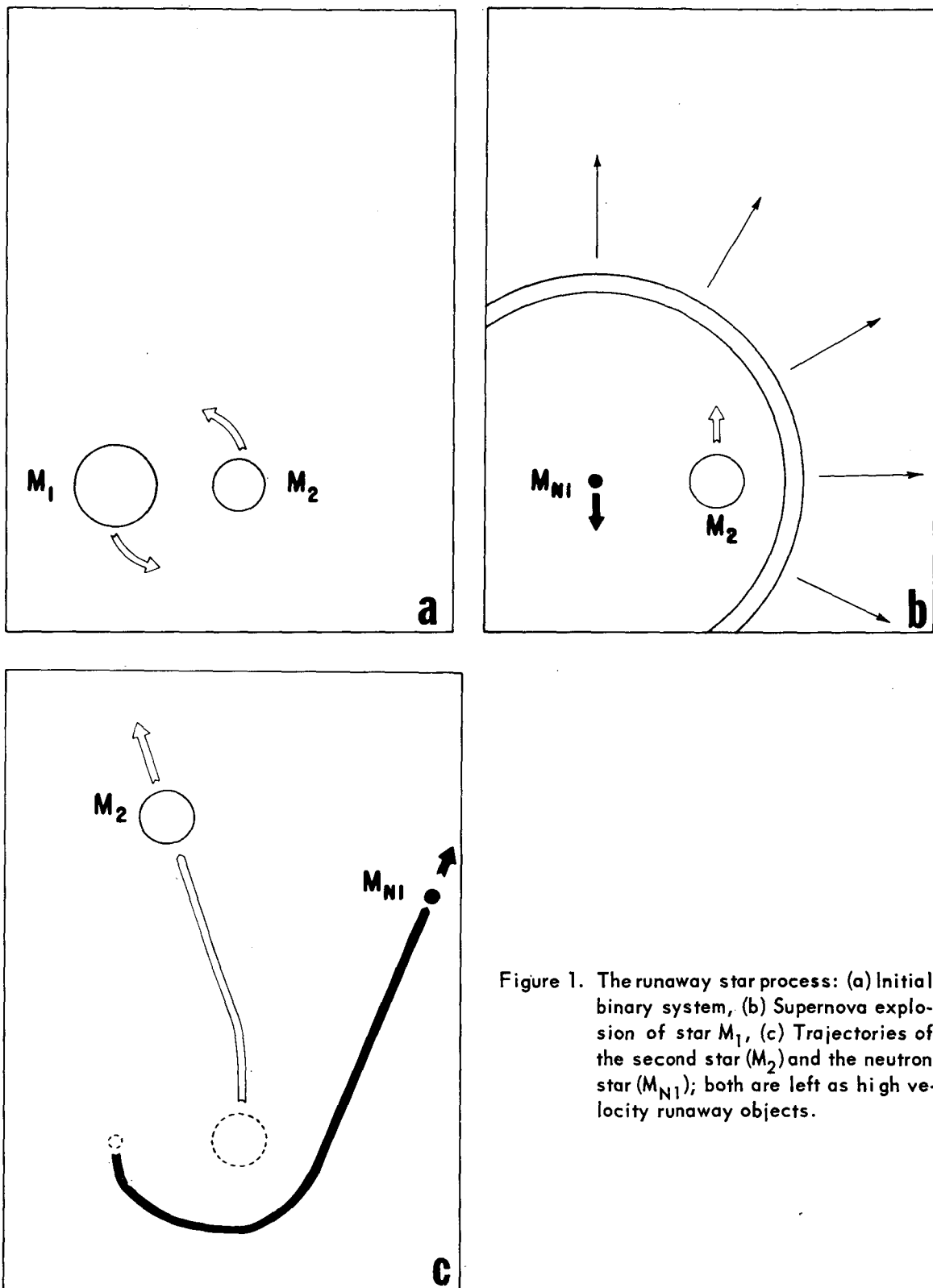


Figure 1. The runaway star process: (a) Initial binary system, (b) Supernova explosion of star M_1 , (c) Trajectories of the second star (M_2) and the neutron star (M_{N1}); both are left as high velocity runaway objects.

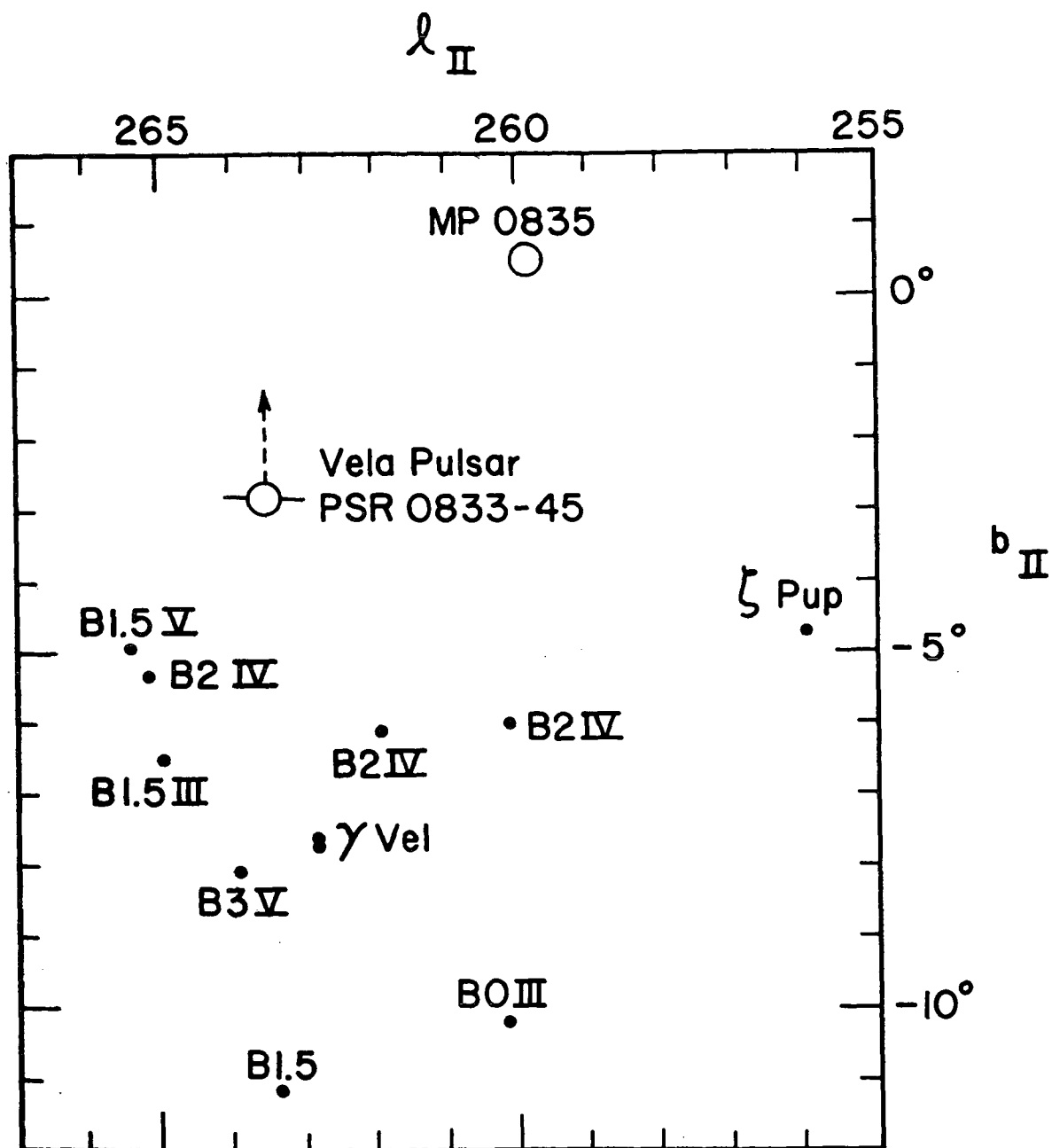


Figure 2. Region of the sky around γ Velorum showing the B association and the two pulsars PSR 0833-45 and MP 0835. Solid line shows the rotation axis of PSR 0833-45 and the dotted line shows its proposed direction of motion

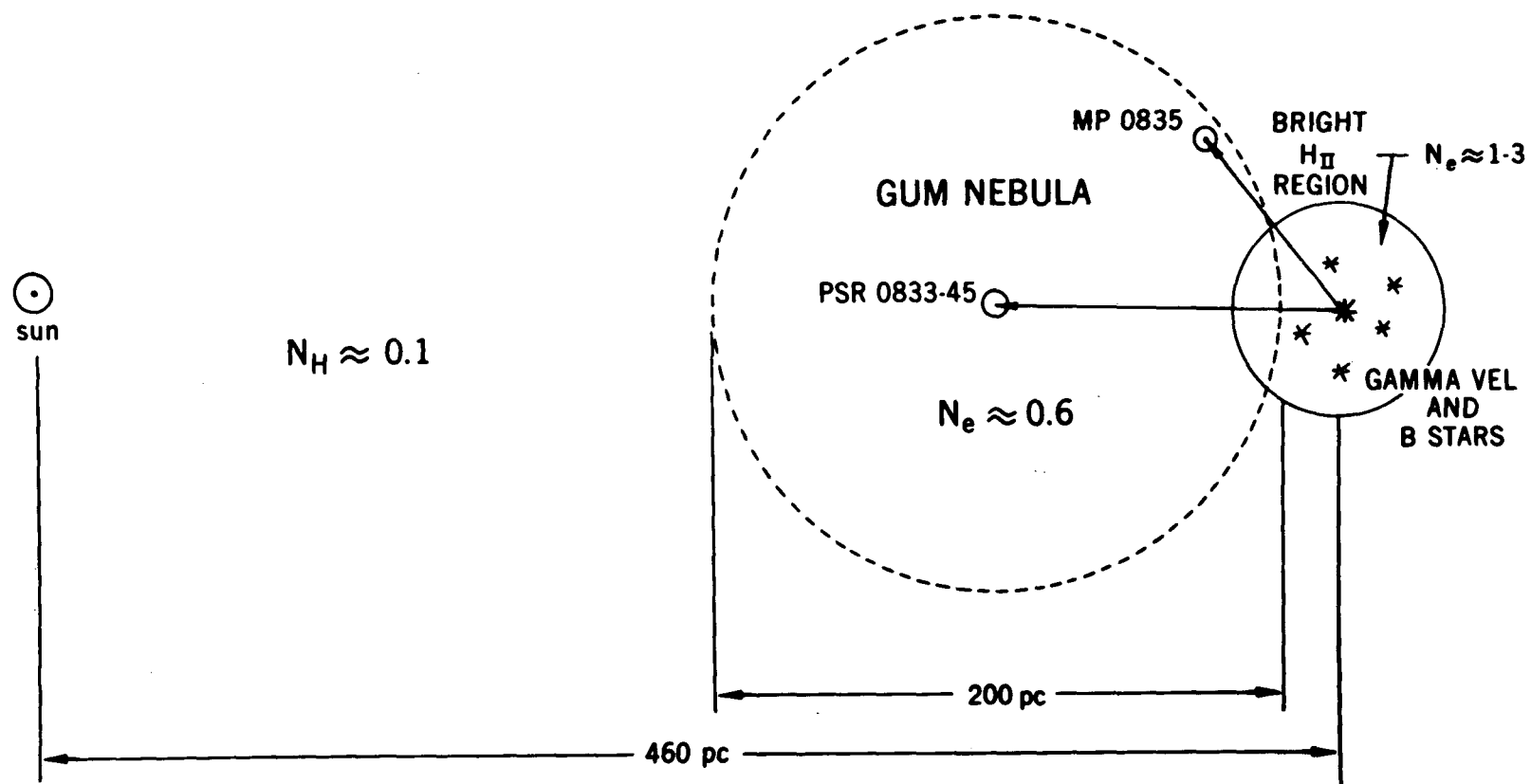


Figure 3. Schematic representation of the adopted model for the Gum Nebula region.

DISCUSSION

A. G. W. Cameron: What made you assume an age of less than 6×10^6 years for MP 0835? Does it concern runaway velocity or a general age theory for pulsars?

J. R. Gott: It is an assumption based on the theory (Gunn and Ostriker) of the upper age limits for pulsars.

Cameron: Then, if we disregard that theory, you could make the age much greater and the pre-supernova masses much lower.

S. A. Colgate: Have you considered the rocket effect when a supernova goes off close to another star? If the mass ratio does not exceed 2 to 1, then at 10^5 km/sec something like 30 times more energy is deposited in the rocket effect than just in the separation of orbits by mass.

Gott: We have not considered the rocket effect.

A. Poveda: It should be pointed out that explosion in a binary system is not the only way to produce runaway stars. They can be produced by dynamical interactions in compact systems. In the Crimean catalog of runaway stars there are about 5 runaway stars in the Gum Nebula region.

Gott: It should also be noted that there are other pulsars in this region that might be runaway objects. We are also checking on Zeta Pup.

S. P. Maran: To me, the most interesting aspect of this paper is the model, which takes the Gum Nebula diameter to be smaller than that derived by Brandt (although it is thereby more in accord with the predictions of Morrison and Sartori), and which takes the Gum Nebula to be closer than derived by Brandt, and to lie in front of the normal H II region around gamma Vel which Bok mentioned. Would someone comment on the acceptability of this model?

J. K. Alexander: This model has to contend with the low-frequency radio measurements. If the nebula had $n_e \approx 0.6 \text{ cm}^{-3}$ and were as close as suggested by Gott and Ostriker, it would be quite opaque at low frequencies. If we divide the observed brightness at a frequency at which it is opaque by the distance at which we no longer get background radiation from beyond the opaque portion of the nebula, then that gives us the volume emissivity of cosmic ray electrons along that path. If we then compare the emissivity thus deduced with the interstellar synchrotron emissivity expected for

cosmic ray electrons, we find the volume emissivity very high compared to direct measurements of cosmic ray electrons. To resolve this apparent discrepancy, we must either raise the nebular temperature so that the path length through the nebula up to the point where it becomes opaque can be increased, or we must increase the distance to the nebula, or we must accept the idea of large spatial gradients in the interstellar cosmic ray electron distribution such that there is an enhanced density of radiating electrons in the vicinity of the Gum Nebula. Although these problems do not make this model impossible, they raise some rather difficult questions.

S. Sobieski: I wonder if the amount of mass loss suggested by the binary star/supernova theory presented here is consistent with the observations, which suggest that the total mass of material in this region is less than one solar mass.

A. B. Underhill: Yes, if the great amount of mass loss mentioned by Gott is distributed in this small region, we ought to be able to see it.

Editor's Note: At this point Dr. A. B. Underhill criticized the pre-supernova masses assumed by Gott as being too high, and Dr. A. G. W. Cameron criticized them as being too low!

Voice: If there are other runaway stars in this region, then why must we suppose that the two pulsars are related to each other as a runaway pair?

Gott: The positions of the two pulsars, both being on the same side of the B-association, and their distances influenced this assumption by us. The rotation axis directions and transverse velocities, when they are known, will be valuable for checking this.

K. Henize: There is no real evidence that these two pulsars are high velocity objects is there?

Gott: No, that is correct. It would be very desirable to obtain such evidence. However, there is statistical evidence that pulsars in general are high velocity objects. First, statistically one finds that old pulsars are further from the galactic equator. Second, the interstellar scintillation observations, such as those of Ewing et al. indicate typical transverse velocities of 100 km/sec for pulsars.